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RESEARCH MEMORANDUM

ALTITUDE-WIND-TUNNEL INVESTIGATION OF A 3000-POUND-THRUST AXIAL-FLOW TURBOJET ENGINE

IV - OPERATIONAL CHARACTERISTICS

By W. Kent Hawkins and Carl L. Meyer

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation has been conducted in the NACA Cleveland altitude wind tunnel to evaluate the operational characteristics of a 3000-pound-thrust axial-flow turbojet engine over a range of simulated altitudes from 2000 to 50,000 feet and simulated flight Mach numbers from 0 to 1.04 throughout the operable range of engine speeds. Operational characteristics investigated include engine operating range, acceleration, deceleration, starting, altitude and flight-Mach-number compensation of the fuel-control system, and operation of the lubrication system at high and low ambient-air temperatures.

The operable range of engine speeds was considerably reduced at altitudes above 40,000 feet. Increasing the flight Mach number at these high altitudes increased the operating range. With one engine configuration, starts were made at windmilling engine speeds up to 7600 rpm at altitudes between 30,000 and 50,000 feet. With the same configuration, minumum engine speeds from which successful starts could be made varied from 1500 rpm at altitudes up to 32,500 feet to 5300 rpm at 50,000 feet. During all accelerations made at altitudes below 25,000 feet, neither combustion blow-out nor excessive compressor surge was encountered. Acceleration from engine speeds below 10,000 rpm at altitudes above 25,000 feet was uncertain and combustion blow-out was frequently encountered. No combustion blow-out was encountered during decelerations at altitudes up to 25,000 feet. During simulated climbs and dives at constant flight Mach number, an approximately constant engine speed was maintained by the governor at constant throttle position with initial engine speeds above 12,000 rpm. At an altitude of 25,000 feet, the engine speed remained essentially constant over the range of flight Mach numbers investigated for initial engine speeds of 11,500 and 12,300 rpm at a constant throttle position. The oil cooler provided adequate cooling at high inlet-air temperatures, and no excessive oil foaming was encountered at altitudes up to 50,000 feet with a 3-pound-per-square-inch pressure-relief valve on the oil-tank vent.

INTRODUCTION

An investigation of an axial-flow turbojet engine having a thrust rating of 3000 pounds has been made in the NACA Cleveland altitude wind tunnel to evaluate the engine operational characteristics over a range of simulated flight conditions. The two engines used in the investigation are referred to as the original and modified engines. The main components of these engines were similar except for changes made within the compressor and the combustion chamber of the modified engine. Analyses of turbine performance, compressor performance, and combustion-chamber performance are presented in references 1, 2, and 3, respectively.

Operational characteristics discussed in this report include engine operating range, acceleration, deceleration, starting, altitude and flight-Mach-number compensation of the fuel-control system, and operation of the lubrication system at high and low ambient-air temperatures. The discussion includes the effect of changes in the fuel system, the oil system, the ignition system, and the combustion chamber on the various operational characteristics.

DESCRIPTION OF ENGINE

The X24C-4B turbojet engine used in this investigation (fig. 1) has a static sea-level rating of 3000 pounds thrust at an engine speed of 12,500 rpm. At this rating, the air flow is approximately 58.5 pounds per second, the fuel consumption is 3200 pounds per hour, and the compressor pressure ratio is 3.8. The over-all length of the engine is $119\frac{1}{2}$ inches, the maximum diameter is $28\frac{1}{4}$ inches, and the total weight is 1150 pounds. The main components of the engine include an 11-stage axial-flow compressor, a double-annulus combustion chamber, a two-stage turbine, and a fixed-area exhaust nozzle.

The main components of the original and modified engines used in the investigation were similar except for changes made to the compressor and the combustion chamber by the manufacturer. As a result of these changes, the limiting turbine-outlet temperature was raised from 1250° to 1400° F as read on the hottest thermocouple. The exhaust-nozzle-outlet area was 183 square inches on the original engine and 171 square inches on the modified engine.

Compressors. - For the compressor of the modified engine, the loading of the eleventh-stage rotor blades was reduced to obtain a more nearly uniform velocity distribution at the compressor outlet. Reduced loading was accomplished by twisting the blades 3° at the mid-span and 6° at the tip in the direction of reduced angle of attack.

926

Combustion chambers. - The only change made to the combustion-chamber basket was in steps 3 and 4. In the original engine, secondary air entered the combustion chamber through rows of circular holes in steps 3 and 4 (fig. 2(a)). For the modified engine, secondary air entered the combustion chamber through a single row of large rectangular holes in step 3 (fig. 2(b)). The total area of the combustion-chamber wall perforations was the same for the original and modified engines. The fuel nozzles for the original engine had a rated capacity of $7\frac{1}{2}$ gallons per hour at a differential pressure of 100 pounds per square inch, as compared to a capacity of 7 gallons per hour for the modified engine. Screens were installed in two of the three annular passages at the combustion-chamber inlet. For the original engine, a screen having 60-percent blocking area was installed in the outer annular air stream and one of 40-percent blocking area was installed in the intermediate annular air stream. For the modified engine, these screens were replaced by two screens of 30-percent blocking area.

Lubrication system. - During most of the investigation, oil was supplied to the engine oil pump from a 50-gallon tank outside the wind-tunnel test section. With this system, the temperature of the oil could be regulated by electric heaters or by a heat exchanger supplied with cooling water. For lubrication and cold-starting tests, a 6-gallon aircraft-type oil tank was mounted above the compressor (fig. 3). For the cold-starting tests, the metering orifices were removed from the oil lines to the bearings, the oil cooler was bypassed, and the standard pressure-relief valve was replaced by one having a greater capacity with two return lines to the tank. Oil conforming to specification AAF 3606 was used for the entire investigation.

Fuel system. - The engine was equipped with a governor unit, which included a gear-type fuel pump, a pressure-relief valve, a speed control, and a barometric control. A schematic diagram of the governor is presented in figure 4 and a description of its operation is included in the appendix. This governor was used only for acceleration, deceleration, and altitude and flight-Mach-number compensation tests. For the remainder of the program, a special fuel-control system was installed (fig. 5). A constant-speed electrically driven gear-type fuel pump was used and fuel was bypassed around the pump by a pressure-relief valve and a throttle in parallel with the relief valve. A throttle in the main fuel line controlled the flow to the fuel manifold. A solenoid drain valve was installed at the bottom of the manifold to drain off the excess fuel when shutting down the engine. Aviation fuel conforming to specification AN-F-28, Amendment 3 was used for the entire investigation.

926

Ignition system. - Ignition was provided by two spark plugs about $1\frac{3}{4}$ inches from the upstream end of the combustion chamber, which entered the bottom of the outer casing at radial angles of 45° with the vertical center line. The standard ingition system supplied with the engine included two ignition coils and two single-electrode spark plugs using the burner basket as the ground electrode with a 0.312-inch spark gap. With the original combustion-chamber basket, a small air gap around the spark plugs allowed air to flow through the sparking region into the primary burning zone. With the modified combustion-chamber basket, shields were provided around the spark plugs (fig. 2(b)) that prevented the flow of air between the plugs and the combustion-chamber basket. The shields then provided the ground electrode.

For part of the starting tests, double-electrode spark plugs were installed in the modified combustion-chamber basket. One set of spark plugs had a spark gap of 0.250 inch and a second set had a spark gap of 0.312 inch. Shields were also provided around these spark plugs that prevented the flow of air between the plugs and the basket.

An electronic ignition system was also used during the starting tests. This system used two double-electrode spark plugs that were supplied with shields. An initial high-frequency impluse of 20,000 to 25,000 volts was used to break down the spark gap and thereby remove carbon from the electrodes. This high-frequency impulse was followed by a relatively low-voltage high-energy impulse that supplied the spark.

INSTALLATION AND PROCEDURE

The engine was installed in a wing nacelle, which was supported in the 20-foot-diameter test section of the altitude wind tunnel by the tunnel balance frame (fig. 6). The engine was supported in the wing by two self-alining ball and socket mounts located on each side of the fuel manifold and by a tie bolt on the top of the front-bearing support.

For part of the investigation, inlet pressures corresponding to high flight Mach numbers were obtained by introducing dry refrigerated air from the tunnel make-up air system through a duct to the engine inlet (fig. 6). This air was throttled from approximately sea-level pressure to the desired pressure at the compressor inlet while the tunnel pressure corresponding to the desired altitude was maintained. The duct from the make-up air system was connected to the engine inlet duct by means of a slip joint with a labyrinth seal.

For acceleration, deceleration, and cold-starting tests, the engine air was taken directly from the wind-tunnel test section (fig. 7). Cowling was installed around the engine and a wooden lip was mounted at the nacelle inlet.

The compressor-inlet air temperature was maintained at approximately NACA standard values for each simulated flight condition, except those of high altitude and low flight Mach number. With the air duct connected to the engine inlet duct, temperatures as low as -20° F were obtained. When the engine air was taken directly from the wind-tunnel test section, temperatures as low as -40° F were obtained.

For the wind-tunnel investigation, an extended tail pipe $20\frac{1}{2}$ inches in diameter and 34 inches long was attached to the downstream flange of the tail-cone casing. An exhaust nozzle 20 inches long was attached to the downstream end of the tail pipe. The exhaust-nozzle-outlet area was 183 square inches for the original engine and 171 square inches for the modified engine.

The operational tests were conducted over a range of simulated altitudes from 2000 to 50,000 feet and simulated flight Mach numbers from 0 to 1.04. Investigation of the lubrication system, except for cold starting, was conducted with the original engine configuration. All other data presented herein were obtained with the modified engine.

Temperatures were measured and recorded by two self-balancing potentiometers. Total and static pressures within the engine were measured by water, alkazene, and mercury manometers and were photographically recorded. Fuel and oil pressures were measured by aircraft selsyn pressure gages. During acceleration and deceleration tests, the engine control panel was photographed at approximately one frame every $1\frac{1}{2}$ seconds by an aerial reconnaissance camera. The engine speed was read from a tachometer except during the operating-range determinations and the altitude and flight-Mach-number compensation tests, when a combination clock and revolution counter was used.

RESULTS AND DISCUSSION

Operating Range

Effects of variation in altitude on the operable range of the modified engine at two different flight Mach numbers are presented in figure 8. The direction in which the altitude and the engine

speed were being changed to obtain data points is indicated by the arrow adjacent to each point. Maximum engine speed was either 12,500 rpm or the speed at which a limiting turbine-outlet temperature of 1400° F, as read on the hottest thermocouple, was obtained. As the altitude was raised at constant flight Mach number, the maximum engine speed decreased. At altitudes above 45,000 feet, burning through the turbine and in the tail pipe was indicated at maximum engine speed by a light blue reflection appearing in the tail pipe. As the flight Mach number was increased at a constant altitude, the maximum engine speed was raised.

Minimum engine speed was defined as the lowest engine speed at which operation was stable and from which the engine could be accelerated. At high altitudes and a constant flight Mach number, the minimum engine speed increased rapidly as the altitude was raised. The minimum engine speed was approximately 4000 rpm at altitudes up to 40,000 feet with a flight Mach number of 0.24 and at altitudes up to 45,000 feet with a flight Mach number of 0.52. Increasing the flight Mach number lowered the minimum engine speed at these altitude conditions.

A limited amount of minimum-engine-speed data obtained with the original engine indicated that at high altitudes the minimum engine speed was considerably lower than for the modified engine. The maximum engine speeds were not appreciably different for the two engines.

Minimum-engine-speed data are not easily reproduced. During operation of the modified engine between 10 and 40 hours after a major overhaul, performance data were obtained in the region indicated as an inoperable range in figure 8. The minimum-speed data were obtained about 110 hours after this overhaul. From these data and similar observations made during the performance investigation, it is concluded that the operating range of the engine changes with engine life.

Acceleration and Deceleration

The turbine-outlet temperature varied during accelerations, although an attempt was made to hold this temperature at the maximum allowable value for acceleration (1500° F as measured by the hottest thermocouple). Careful manipulation of the throttle was required between engine speeds of 4000 and 6000 rpm to avoid exceeding the temperature limit. Above an engine speed of 6000 rpm, the throttle was opened wide, but in most cases the governor limited the acceleration to temperatures below the limiting value.

The effect of altitude on the acceleration characteristics of the modified engine with the engine governor installed is presented in figures 9 and 10. During all accelerations made at altitudes below 25,000 feet, neither combustion blow-out nor excessive compressor surge was encountered. Acceleration from engine speeds below 10,000 rpm at altitudes above 25,000 feet was uncertain and combustion blow-out was frequently encountered as a result of erratic governor operation. At an altitude of 35,000 feet, combustion blow-out was repeatedly encountered during rapid accelerations from engine speeds of 8000 and 9000 rpm.

The time required at static flight conditions to accelerate from 6000 to 11,500 rpm increased from 8 seconds at 5000 feet to 16.8 seconds at 25,000 feet (fig. 10). This increase in acceleration time with altitude resulted from the decreased accelerating force exerted on the turbine blades by the low-density gases at high altitude. The results of experimental and calculated data to determine the ratio of the time required to accelerate at altitude to the time required at sea level are shown in figure 11. In determining the calculated curve, the effects of friction were neglected and the assumption was made that turbine-inlet temperatures were the same at all altitudes during acceleration. The ratio of time required to accelerate at altitude to that required at sea level was then found to be inversely proportional to the respective densities of the inlet air.

The effect of flight Mach number on the acceleration time at an altitude of 5000 feet is shown in figure 12 for accelerations from two different engine speeds. An increase in flight Mach number from 0 to 0.45 reduced by about 19 percent the time required to accelerate the engine from 4000 to 12,000 rpm and reduced by about 16 percent the time required to accelerate from 6000 to 12,000 rpm. A reduction in acceleration time with increase in flight Mach number was observed at altitudes up to 25,000 feet. All acceleration data presented herein could be duplicated. Due to erratic governor action, some accelerations were made at greater rates without exceeding exhaust-gas temperature limits; when attempts were made to duplicate these accelerations, however, excessive temperatures were encountered.

The minimum time required for a deceleration was obtained by moving the throttle to the full-closed position and holding it there until the engine idling speed of 4000 rpm was reached. The throttle was then advanced to maintain this idling speed. The effect of change in altitude on the rate at which the modified engine could be decelerated is shown in figure 13. Combustion blow-out was not encountered during any deceleration at altitudes up to 25,000 feet. The time required to decelerate from an engine speed of 12,000 to 4000 rpm increased from about 10.5 seconds at 5000 feet to about 40 seconds at 25,000 feet.

The increased time required to decelerate the engine at high altitudes was partly due to the reduction in windage losses resulting from the lower air density.

The effect of flight Mach number on the deceleration time at an altitude of 25,000 feet is shown in figure 14. An increase in flight Mach number from 0 to 0.45 decreased by about 21 percent the time required to decelerate the engine from 12,000 rpm to 4000 rpm. Most of the decrease in decelerating time occurred between engine speeds of 11,000 and 6000 rpm. A reduction in decelerating time with increases in flight Mach number was observed at all altitudes below 25,000 feet, which is partly attributed to an increase in windage losses due to higher air density at the compressor inlet. No decelerations were made at altitudes above 25,000 feet due to erratic governor operation.

Altitude and Flight-Mach-Number Compensation of Engine-Governor System

Simulated climbs and dives were made at constant flight Mach number between altitudes of 5000 and 40,000 feet with the modified engine. The altitude limit of each climb was that altitude at which limiting turbine-outlet gas temperatures were encountered.

Above an initial engine speed of 12,000 rpm with a constant throttle position, the governor maintained an approximately constant engine speed as the altitude was increased, whereas at lower initial speeds, the speed increased as the altitude was raised (fig. 15). The governor was designed to allow an increase in engine speed from low initial speeds as the altitude was raised, as shown in figure 15. Although this effect was obtained, governor action was not completely satisfactory because limiting gas temperatures at the turbine outlet were encountered between altitudes of 30,000 and 40,000 feet. This condition resulted from inability of the governor to keep engine speeds within the operable range. The hysteresis in the governor during climbs and dives was negligible at high initial engine speeds, but at initial engine speeds below 8000 rpm this effect was appreciable.

During simulated climbs and dives, irregular action of the governor barometric control caused hunting at certain fuel flows and bands of engine speeds. The amplitude of this hunting usually amounted to about 200 rpm, with an oscillation period of about 2 to 4 seconds. Conditions at which this hunting took place were not clearly defined.

Effects of variations in flight Mach number from 0.11 to 1.04 on speed regulation are shown in figure 16 for an altitude of 25,000 feet. The engine speed remained essentially constant over the range of flight Mach numbers investigated for engine speeds of 11,500 and 12,300 rpm. For an initial engine speed of 9050 rpm, the maximum deviation was 350 rpm for the range of flight Mach numbers investigated. Negligible hysteresis effects were encountered at all engine speeds.

Violent hunting of engine speed and fuel flow often occurred at engine speeds of about 12,000 rpm as the flight Mach number was being increased. In one case, at an altitude of 25,000 feet and a flight Mach number of about 1.04, the engine speed suddenly surged from 12,400 to 13,000 rpm and it was therefore necessary to pull back the throttle.

Starting Characteristics

<u>Original-engine combustion-chamber basket.</u> - With the original-engine combustion-chamber basket, which had an air gap around the spark plugs through which air was admitted to the primary burning zone, erratic starting characteristics were observed. Starting at sea-level static conditions was fairly dependable, although the turbine-outlet gas temperatures were often considerably above limits during the acceleration to engine idling speed. This condition was caused by an excess of fuel in the combustion chamber as a result of delayed burner ignition during the starting attempt.

Windmilling starting characteristics were very unsatisfactory because the combustion chamber could not be ignited at a windmilling engine speed of more than 1000 rpm at an altitude of 5000 feet. The starter cranking speed of the engine was found to be approximately 1500 rpm, thereby making it impossible to ignite the combustion chamber at an altitude of 5000 feet with the starter in use. Starts were made at altitude by igniting the combustion chamber at engine windmilling speeds under 1000 rpm and then engaging the starter to assist in acceleration.

<u>Modified-engine combustion-chamber basket.</u> - With the modified-engine combustion-chamber basket, in which the only change made to the primary burning zone was sealing the gap around the spark plugs, starting characteristics were satisfactory. Starting at sea-level static conditions was dependable and acceleration was easily accomplished.

The windmilling starting data presented were obtained with the electronic ignition system. The minimum engine windmilling speeds

from which successful starts could be made varied from approximately 1500 rpm at altitudes up to 32,500 feet to 5300 rpm at 50,000 feet (fig. 17). Engine windmilling speeds of 1500 and 5300 rpm correspond to flight Mach numbers of about 0.30 and 0.90, respectively. Below an altitude of 40,000 feet, starts could be made at engine windmilling speeds lower than indicated in figure 17, but acceleration was difficult and turbine-outlet gas temperatures were excessive. Starts were made at windmilling speeds up to about 7600 rpm at altitudes as high as 50,000 feet, but no starts were attempted above this speed.

Improved starting characteristics with the modified combustion-chamber basket could probably be attributed to sealing of the air gap around the spark plugs, inasmuch as air passing through the gap in the original basket tended to blow the fuel away from the spark plugs.

Ignition Systems

Ignition coil and single-electrode spark plug. - With the single-electrode unshielded spark plugs having a spark gap of 0.312 inch, which were installed in the original combustion-chamber basket, no starts were attempted at altitudes above 10,000 feet. It might have been possible to ignite the fuel in the combustion chamber with this spark-plug configuration at high altitudes; however, because no starts could be made at windmilling speeds above 1000 rpm, excessively high turbine-outlet temperatures would have been encountered. With the single-electrode shielded spark plugs, which were installed in the modified combustion-chamber basket, starts were made at altitudes up to 40,000 feet.

Ignition coil and double-electrode spark plug. - With the double-electrode shielded spark plugs having a spark gap of 0.250 inch, which were installed in the modified-engine combustion-chamber basket, starts were made at altitudes up to 40,000 feet. A number of attempts to start the engine at an altitude of 45,000 feet with this configuration were unsuccessful. When the spark gap was increased to 0.312 inch, it was impossible to start the engine at any altitude.

Electronic ignition system and double-electrode spark plug. - With the electronic ignition system and the double-electrode spark plugs installed in the modified-engine combustion-chamber basket, starts were made at altitudes up to 50,000 feet. When the energy supplied to the spark plugs was reduced below the normal level, starting was not always possible at an altitude of 50,000 feet. No starts were attempted at altitudes above 50,000 feet.

926

Lubrication System

Oil foaming. - The oil-foaming problem was investigated with the original engine at altitudes up to 50,000 feet throughout the range of operable engine speeds with the 6-gallon oil tank attached to the engine installation. With a 3-pound-per-square-inch pressure-relief valve on the oil-tank vent, no oil consumption due to foaming in the tank was encountered at any altitude. Oil-pump discharge pressure increased as the altitude was raised and thereby afforded sufficient pressure to lubricate the engine adequately at all altitudes. The increase in pressure was attributed to the decrease in ambient-air temperature, which lowered the oil temperature.

Oil cooling. - An investigation was conducted with the original engine at elevated compressor-inlet temperatures in order to determine whether the oil cooler had adequate capacity to cool the oil at high ambient-air temperature and high flight speed and thus prevent the bearings from overheating. With an inlet-air temperature of 107° F at an altitude of 35,000 feet, a flight Mach number of 1.04, and an engine speed of 12,500 rpm, the oil-pump discharge temperature stabilized at 141° F. Because adequate cooling was provided by the oil cooler, the stabilized bearing temperatures ranged from 138° F on bearing 1 to 215° F on bearing 3. The maximum allowable bearing temperatures are 200° F for bearing 1 and 285° F for bearings 2 and 3.

Cold starting. - In starting the engine at subzero temperatures, the critical component is the lubrication system. At such low temperatures, the high viscosity of the oil may result in failure of the oil pump, excessive bearing temperatures, or both. An oil line was so installed that the oil cooler was bypassed and the capacity of the pressure-relief valve was increased. Before a cold start, the engine was allowed to soak at an ambient-air temperature of about -50° F at an altitude of 2000 feet until the bearing temperatures were within about 20° F of the ambient-air temperature.

Data showing the increase in engine speed and oil-pump discharge pressure with time during two cold starts with the modified engine are shown in figure 18. On the first start, the engine speed was increased to about 7000 rpm in 43 seconds, at which time the oil pump failed, as indicated by the drop in oil-pump discharge pressure. Inspection of the oil pump revealed that expansion of the rotors resulted in seizure due to inadequate axial clearance and caused the drive shaft to shear.

A replacement oil pump with increased axial clearance was installed on the engine. For the cold start made with this pump, the engine speed was increased at a slower rate in order to avoid

exceeding an oil-pump discharge pressure of 300 pounds per square inch (fig. 19(a)). Approximately 9 minutes were therefore required to reach an engine speed of 12,400 rpm. After 13 minutes of operation, the oil-pump discharge pressure had stabilized. No excessive bearing temperatures were encountered during the cold start (fig. 19(b)) and the temperatures stabilized after approximately 23 minutes of operation. 926

Because of the slower acceleration, the replacement oil pump was not subjected to as severe treatment as the original pump. Failure of the original pump might not have occurred had the acceleration been slower.

SUMMARY OF RESULTS

From an investigation of a complete axial-flow turbojet engine with a thrust rating of 3000 pounds in the NACA Cleveland altitude wind tunnel at simulated conditions of altitude and flight Mach number, the operational performance is summarized as follows:

1. The operating range was considerably reduced at altitudes above 40,000 feet. Increasing the flight Mach number at these high altitudes increased the operable range of engine speed.

2. With the modified-engine combustion-chamber basket and the electronic ignition system, starts were made at windmilling speeds up to 7600 rpm at altitudes up to 50,000 feet; however, no starts were attempted at higher windmilling speeds. The minimum engine windmilling speed from which successful starts could be made varied from 1500 rpm at altitudes up to 32,500 feet to 5300 rpm at 50,000 feet.

3. During all accelerations made at altitudes below 25,000 feet, neither combustion blow-out nor excessive compressor surge was encountered. Acceleration from engine speeds below 10,000 rpm at altitudes above 25,000 feet was uncertain and combustion blow-out was frequently encountered as a result of erratic governor operation.

4. No combustion blow-out was encountered during decelerations at altitudes up to 25,000 feet. No decelerations were made at higher altitudes.

5. Above an initial engine speed of 12,000 rpm with a constant throttle position, the governor maintained an approximately constant engine speed as the altitude was increased. At lower initial engine speeds, the speed increased as the altitude was raised until high speeds that were limited by turbine-outlet gas temperatures were encountered between altitudes of 30,000 and 40,000 feet.

6. At a constant throttle position, the engine speed remained essentially constant over the range of flight Mach numbers investigated at an altitude of 25,000 feet for engine speeds of 11,500 and 12,300 rpm.

926

7. No excessive oil foaming was encountered at altitudes up to 50,000 feet with a 3-pound-per-square-inch pressure-relief valve on the vent of a 6-gallon aircraft-type oil tank. Adequate oil cooling was provided by the oil cooler at compressor-inlet air temperatures up to 107° F at an altitude of 35,000 feet.

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APPENDIX - FUNCTIONING OF STANDARD ENGINE GOVERNOR

The standard engine governor consists of a gear-type fuel pump in conjunction with an all-speed governor, an acceleration and deceleration control, and an altitude and flight-Mach-number compensation control. The governor is driven directly from the accessory-drive gearbox and is mounted on the gearbox. 926

A schematic diagram of the governor is presented in figure 4. The main flow of fuel supplied by the fuel pump B passes through the venturi D, the throttle orifice F, the constant-pressure valve G, and the manifold pressure valve H into the engine fuel-nozzle manifold system. Pump outlet pressure is held constant by the relief valve C, bypassing fuel to the pump inlet. The displacement of the pump and hence the fuel flow is a function of the engine speed. Because the entire capacity of the gear-type fuel pump passes through the venturi, the pressure drop across the venturi is a function of the engine speed. This pressure drop is applied to the control diaphragm I, which is loaded by the pilot-valve spring K, the force of which is determined by a cam N located on the shaft of the control arm M. Thus it can be seen that each position of the control arm requires a certain engine speed for the system to be balanced. In this manner the speed-measuring part of the control is provided.

The pilot valve J, which is located on the shaft between the control diaphragm and the pilot-valve spring, controls the fuel pressure bled throught the pilot-valve jet L from the spring side of the constant-pressure valve G. The position of the constant-pressure valve is therefore governed by movement of the control diaphragm, which in turn controls the amount of fuel to the engine.

Downstream of the constant-pressure valve, some of the fuel that would otherwise go into the combustion chamber is bypassed through the acceleration control O back to the inlet side of the pump. The acceleration control performs a dual function; it provides a fixed acceleration curve to permit engine acceleration at a safe rate and it compensates for changes in altitude and airspeed to enable the governor to maintain a constant engine speed for a fixed control-arm position.

The first function is accomplished as follows: The size of the throttle orifice and the rates of the relief-valve, the constant-pressure-valve and manifold-pressure-valve springs, are chosen so that during most of the acceleration process all the pump delivery, except that bypassed by the acceleration control, must go to the engine. The pressure downstream of the constant-pressure valve is communicated to the end of the acceleration-control valve P

opposite its spring through the bleed holes in this valve. When this pressure reaches a sufficient value, it moves the valve toward an open position until the bleed ports are sealed by the center land of the acceleration-control servo valve. The valve then provides (at constant compressor-inlet pressure) a fixed-area bypass that returns to the fuel-pump inlet the fuel not needed for acceleration. The size of the bypass opening in the acceleration control is governed by an aneroid capsule S, which is subjected to compressor-inlet pressure R.

The second function of this control is explained as follows: With increasing altitude and constant flight speed, the aneroid-capsule-chamber pressure is reduced, therefore causing the capsule to expand. This action moves the accelerating-control servo valve Q, and thereby permits the acceleration-control valve to open further. This increase in bypass opening permits more fuel to return to the pump inlet and thus reduces the fuel supplied to the engine. The control diaphragm, the pilot valve, and the pilot-valve spring can thus maintain approximately the relative position they had at sea level. The impact pressure of forward airspeed causes the capsule to work in the reverse direction, which permits less fuel to return to the pump inlet and thus increases the fuel supplied to the engine.

The manifold-pressure valve H establishes a minimum internal pressure in the control. This pressure is required in order to insure a sufficient pressure drop across the acceleration-control valve at altitude, to allow it to bypass back to the fuel-pump inlet the amount of fuel not required by the engine at that altitude.

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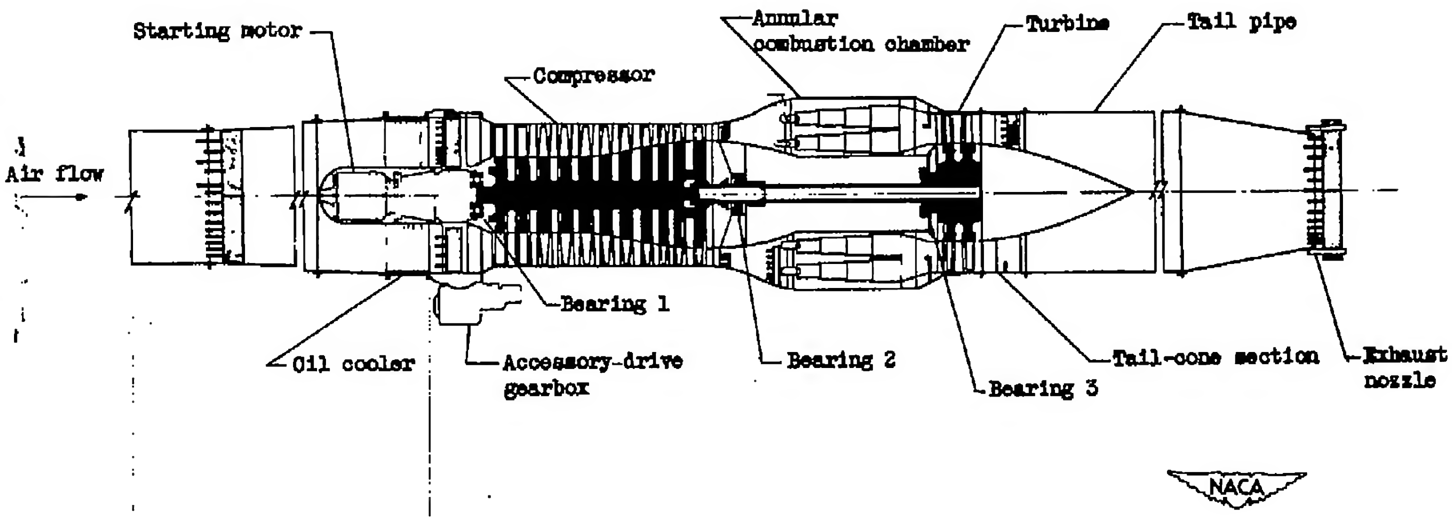
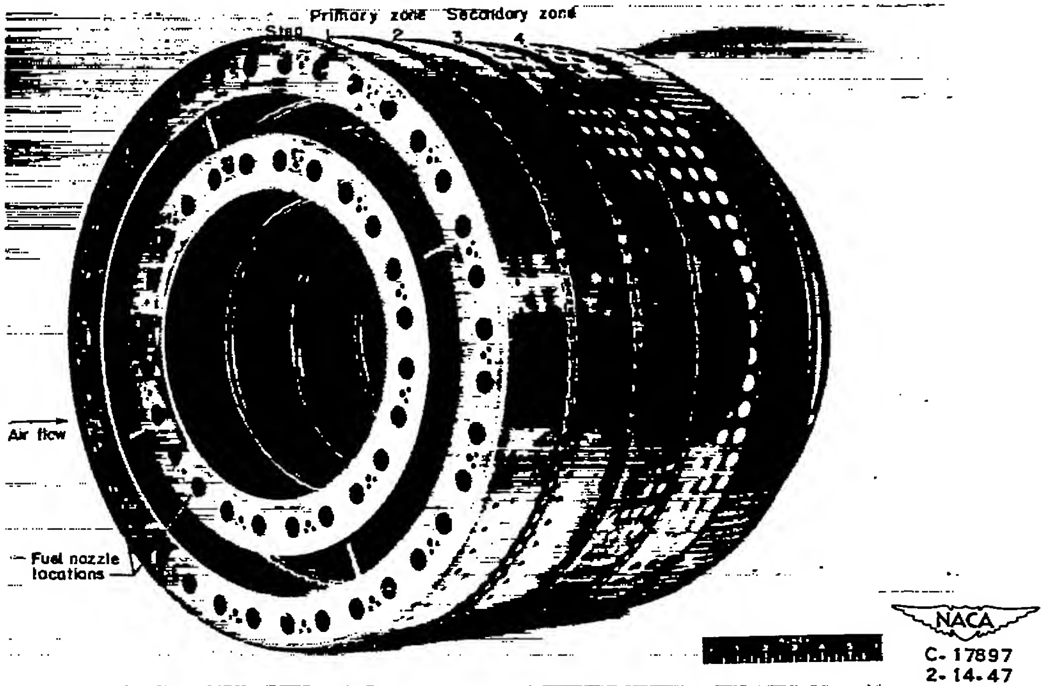
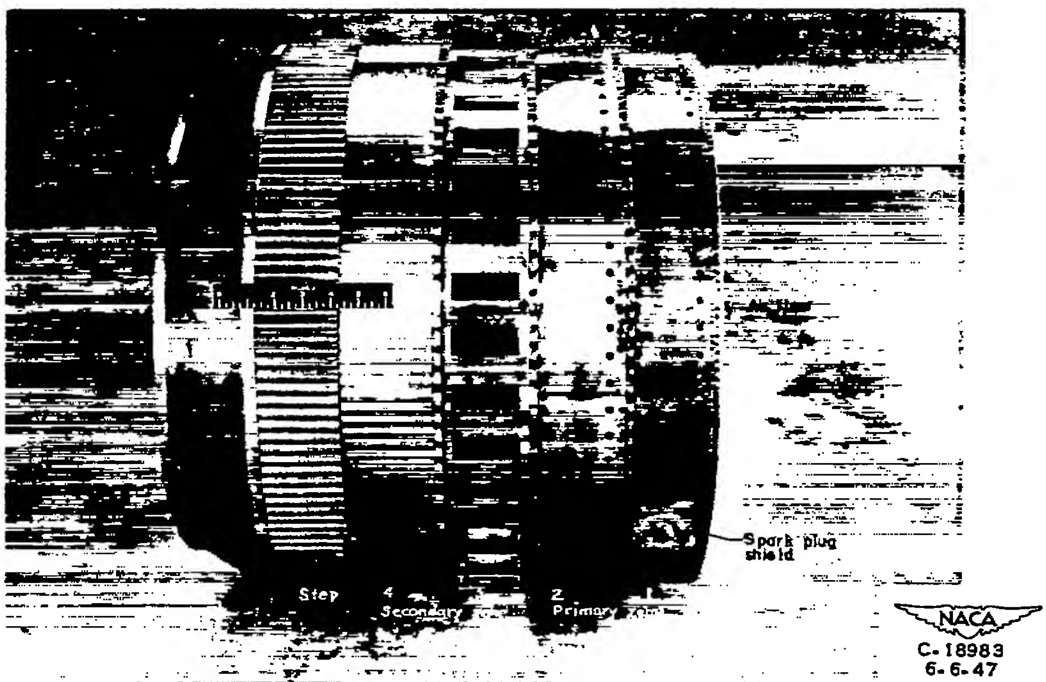


Figure 1. - Sectional view of turbojet-engine installation showing component parts.



(a) Original-engine basket.



(b) Modified-engine basket.

Figure 2. - Combustion-chamber baskets of turbojet engine.

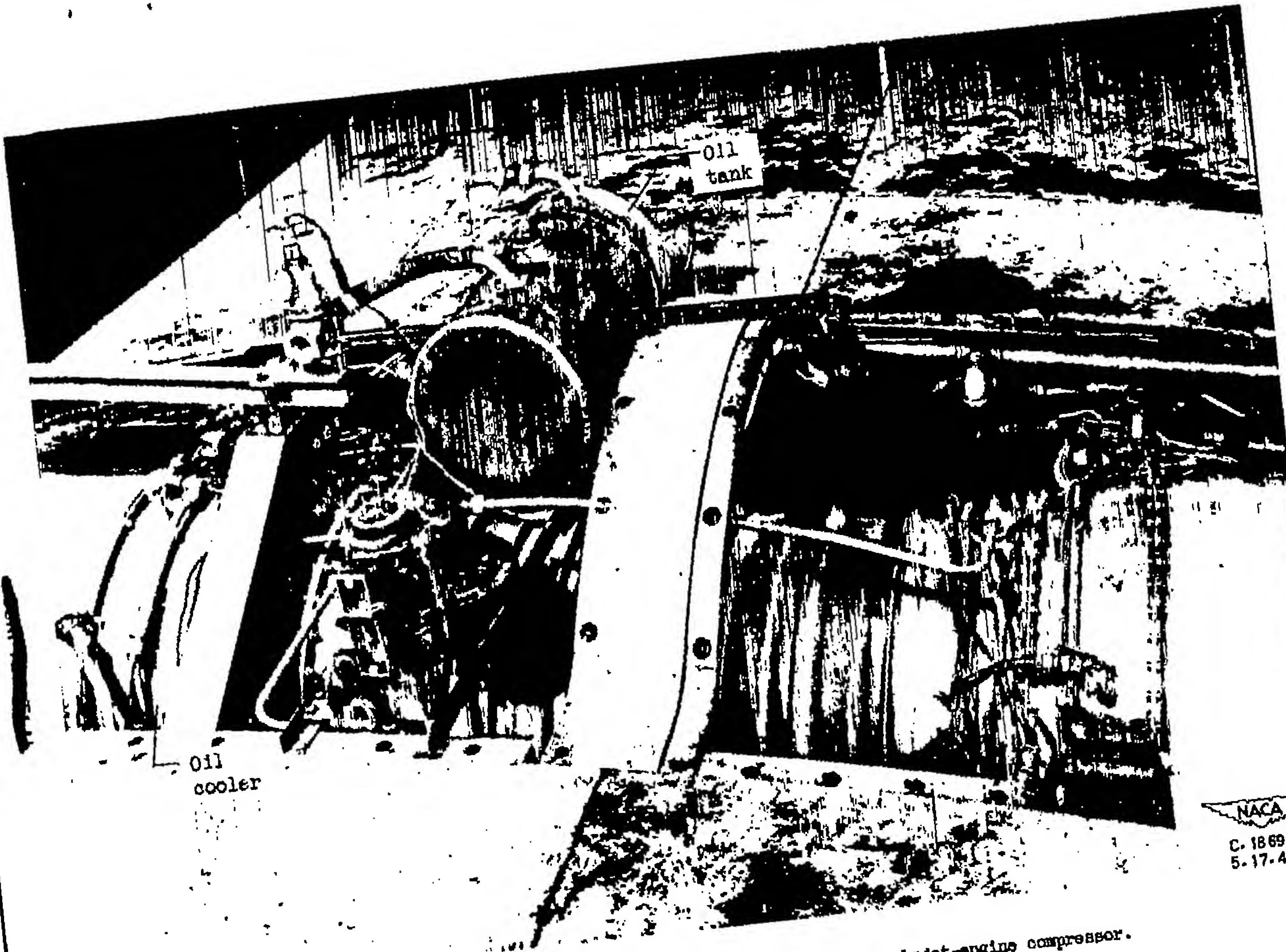


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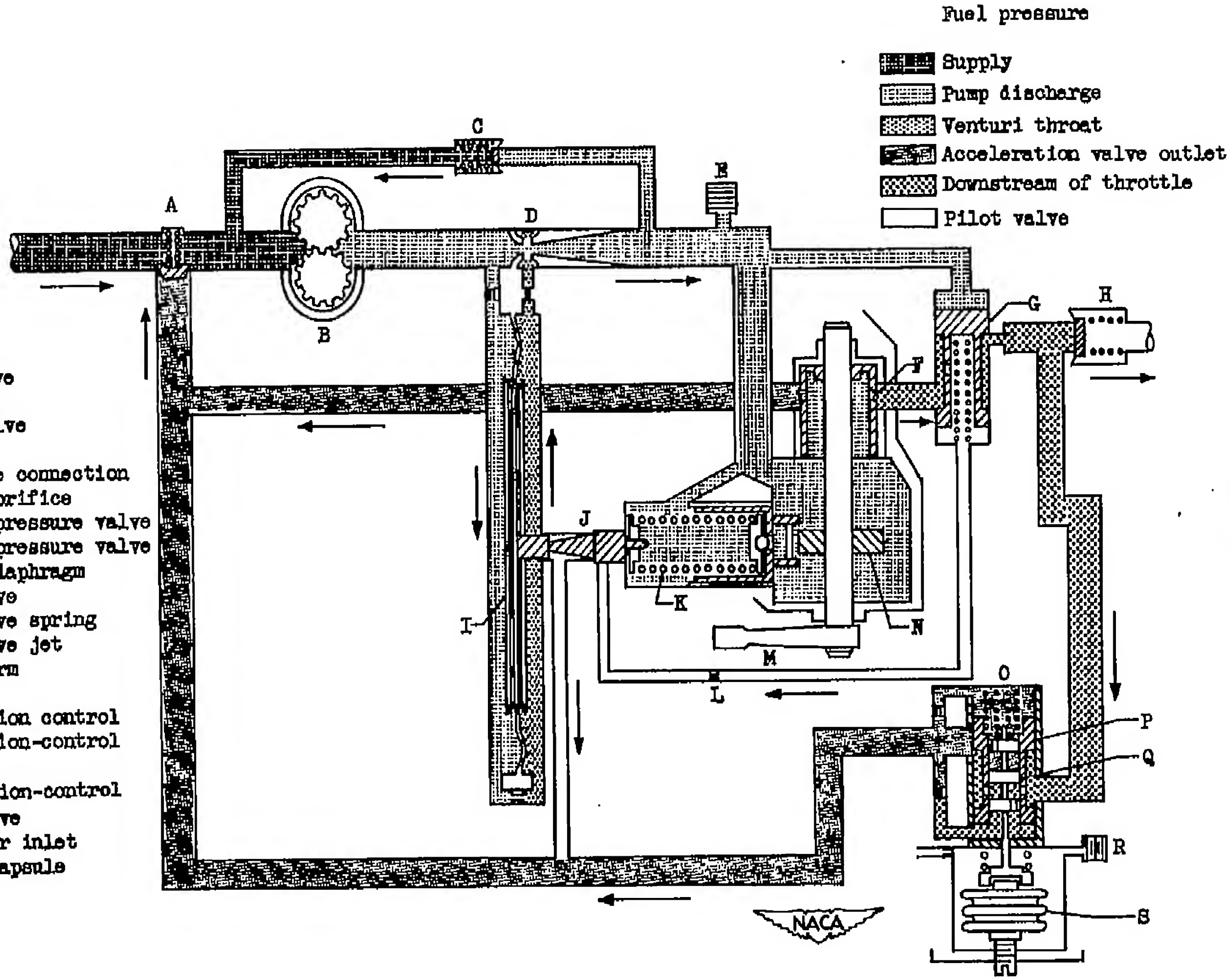
Figure 3. - Aircraft-type oil-tank installation mounted over turbojet-engine compressor.



A Check valve
B Fuel pump
C Relief valve
D Venturi
E Dump-valve connection
F Throttle orifice
G Constant-pressure valve
H Manifold-pressure valve
I Control diaphragm
J Pilot valve
K Pilot-valve spring
L Pilot-valve jet
M Control arm
N Cam
O Acceleration control
P Acceleration-control valve
Q Acceleration-control servo valve
R Compressor inlet
S Aneroid capsule

Figure 4. - Schematic diagram of turbojet-engine governor used in investigation.

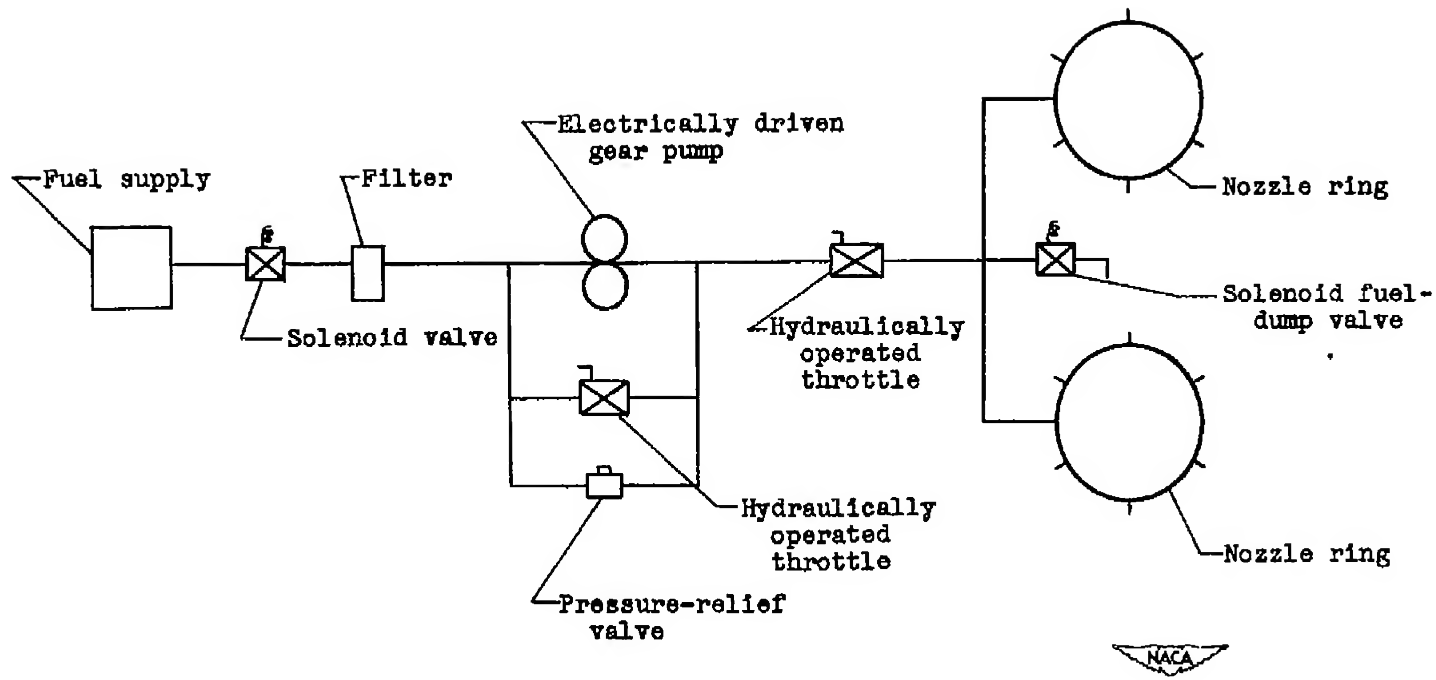


Figure 5. - Schematic diagram of special fuel-control system used with turbojet engine.

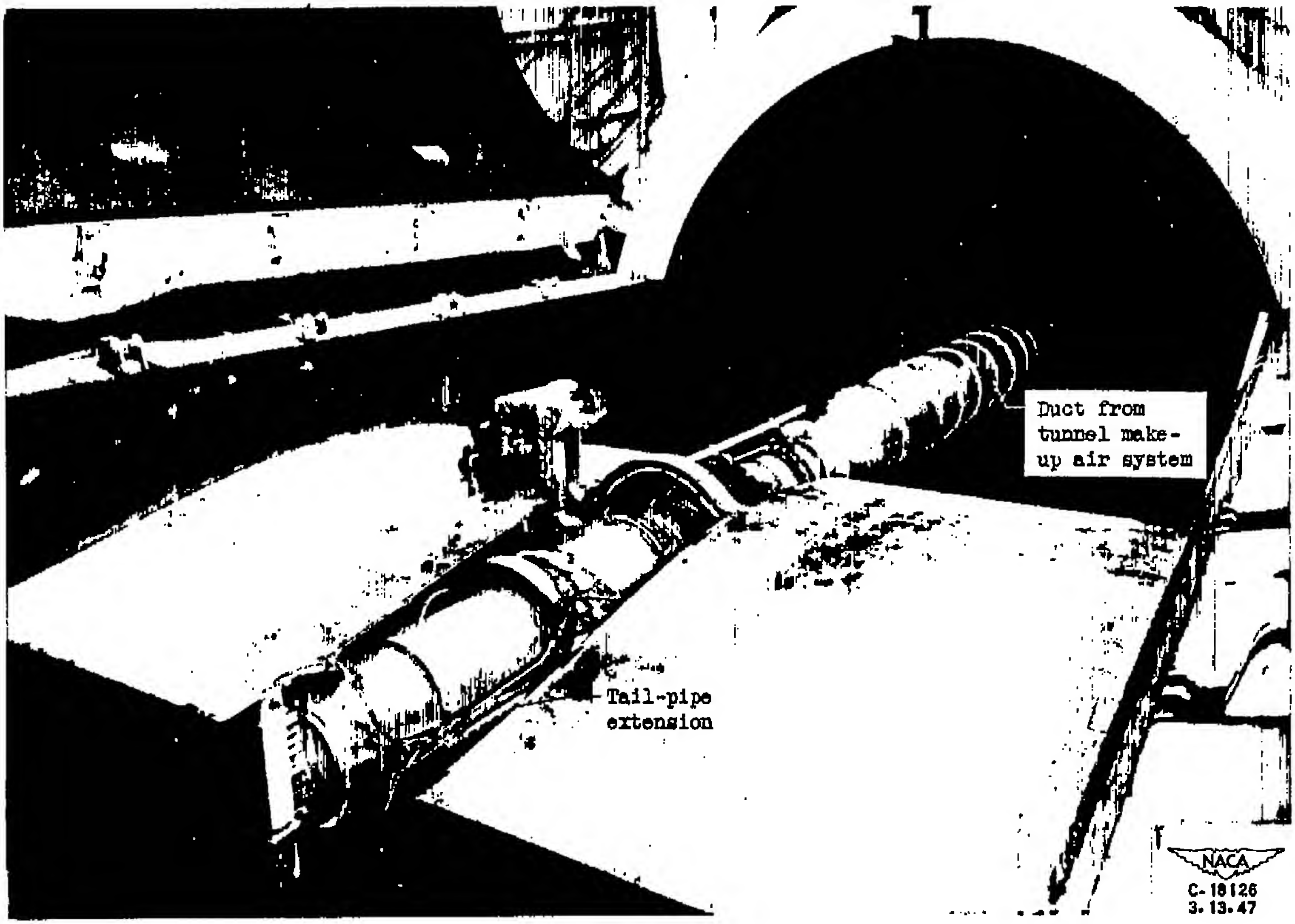


Figure 6. - Wing-nacelle installation of turbojet engine in 20-foot-diameter test section of altitude wind tunnel showing make-up air duct and tail-pipe extension.

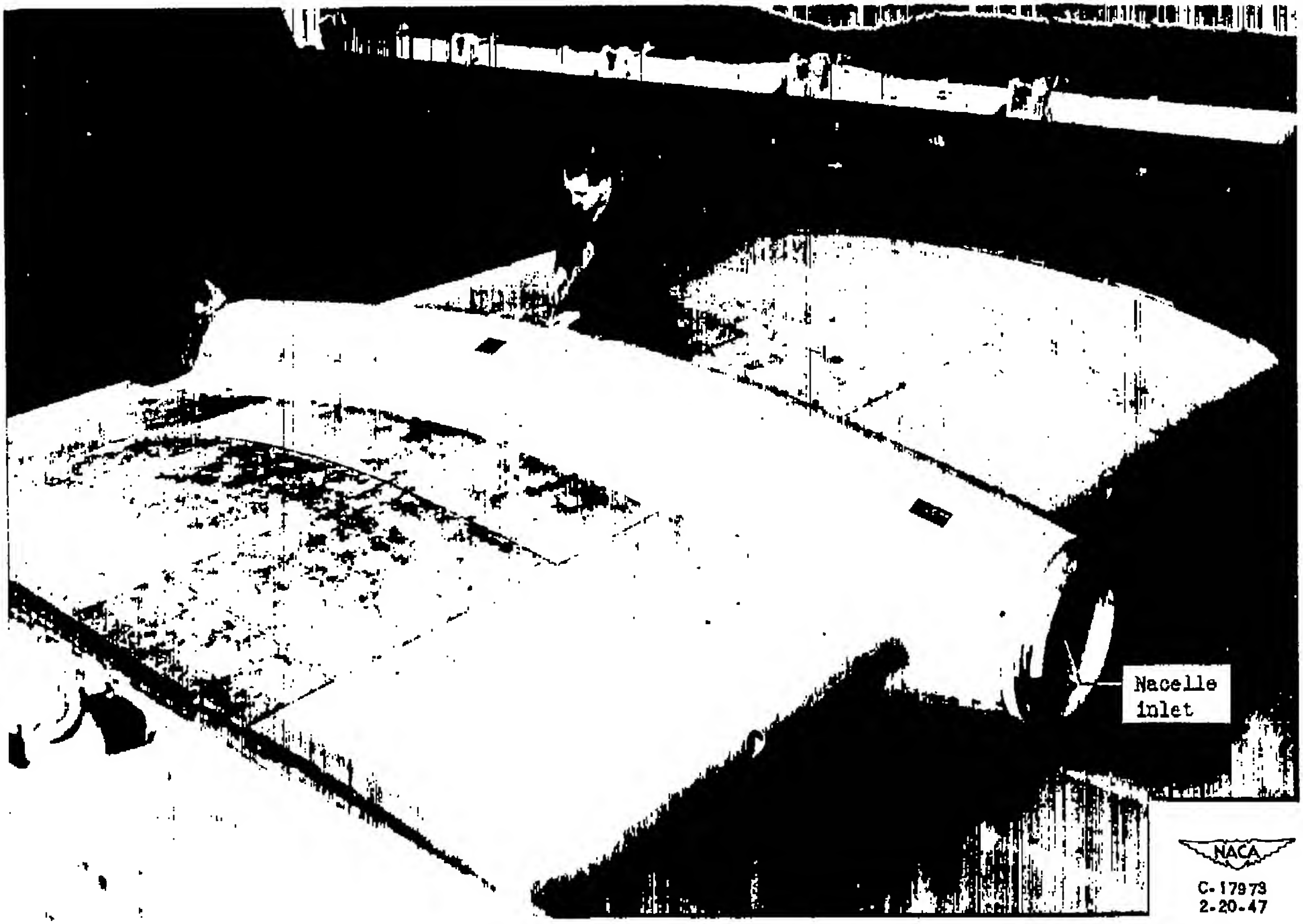


Figure 7. - Wing-nacelle installation of turbojet engine in test section of altitude wind tunnel showing nacelle-inlet duct lip and complete cowling.

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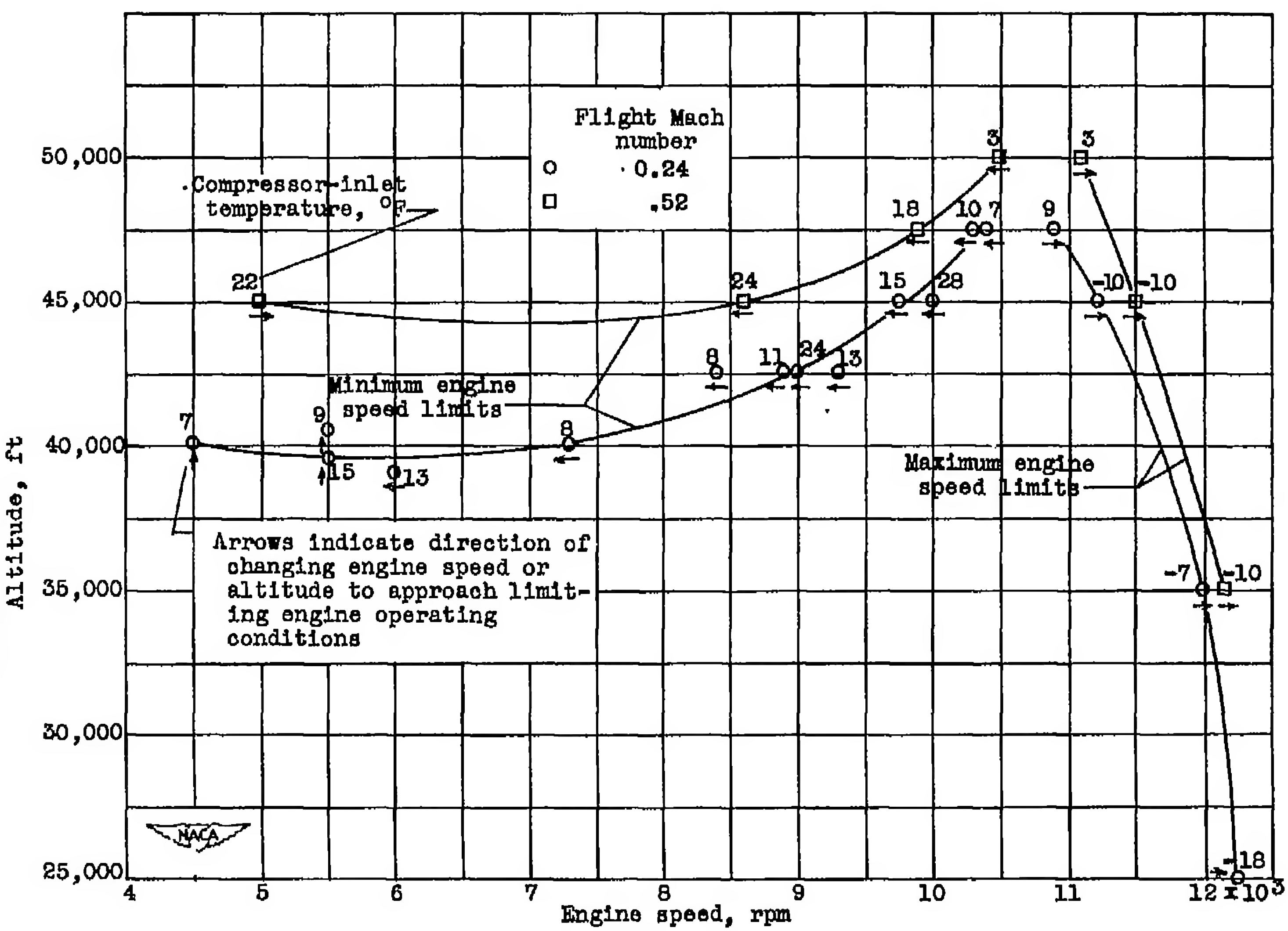

Figure 8. - Effect of altitude and flight Mach number on operating range of modified engine with special fuel-control system.

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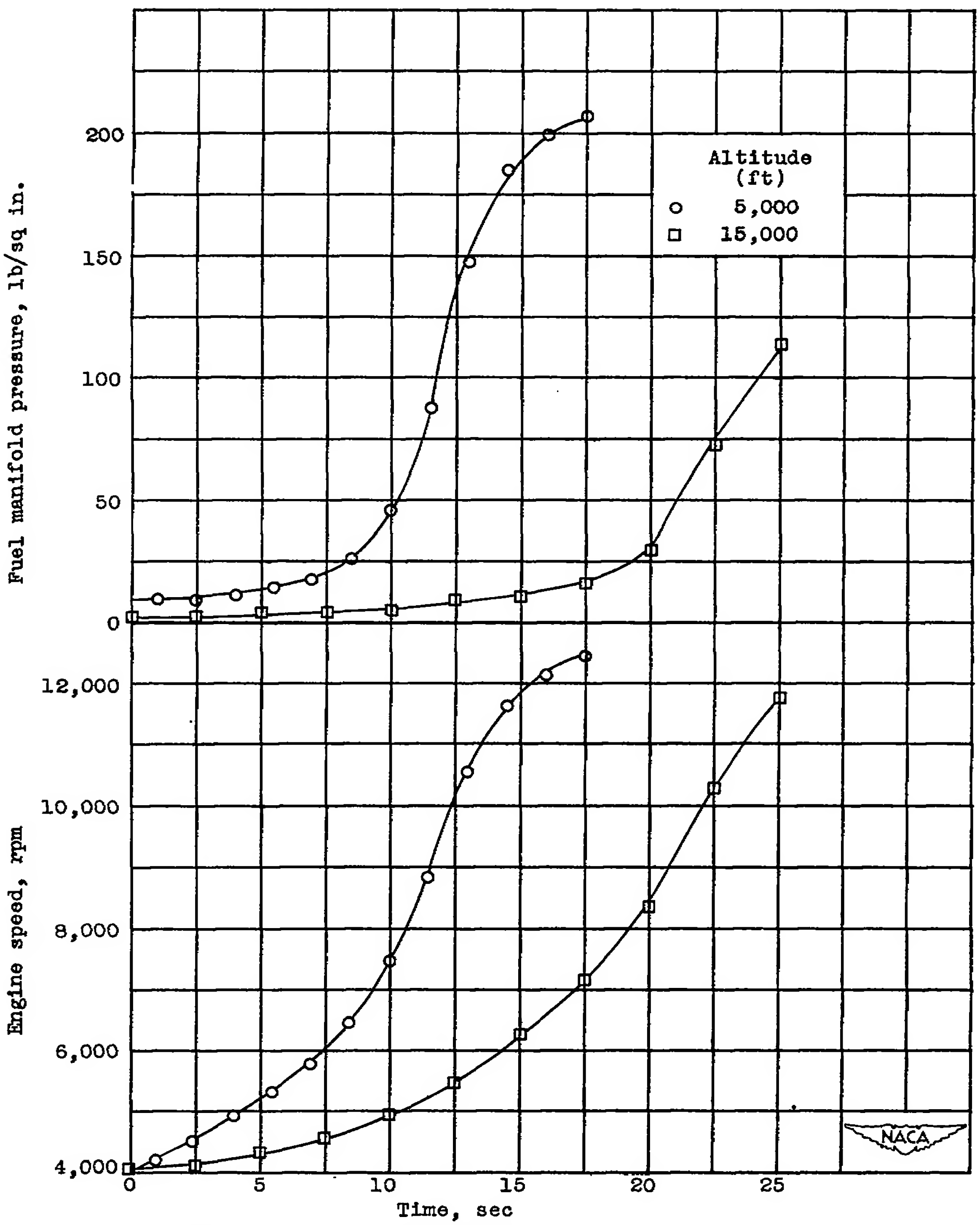

Figure 9. - Effect of altitude on time required to accelerate from idling speed to 12,000 rpm at flight Mach number of 0. Modified engine with engine governor.

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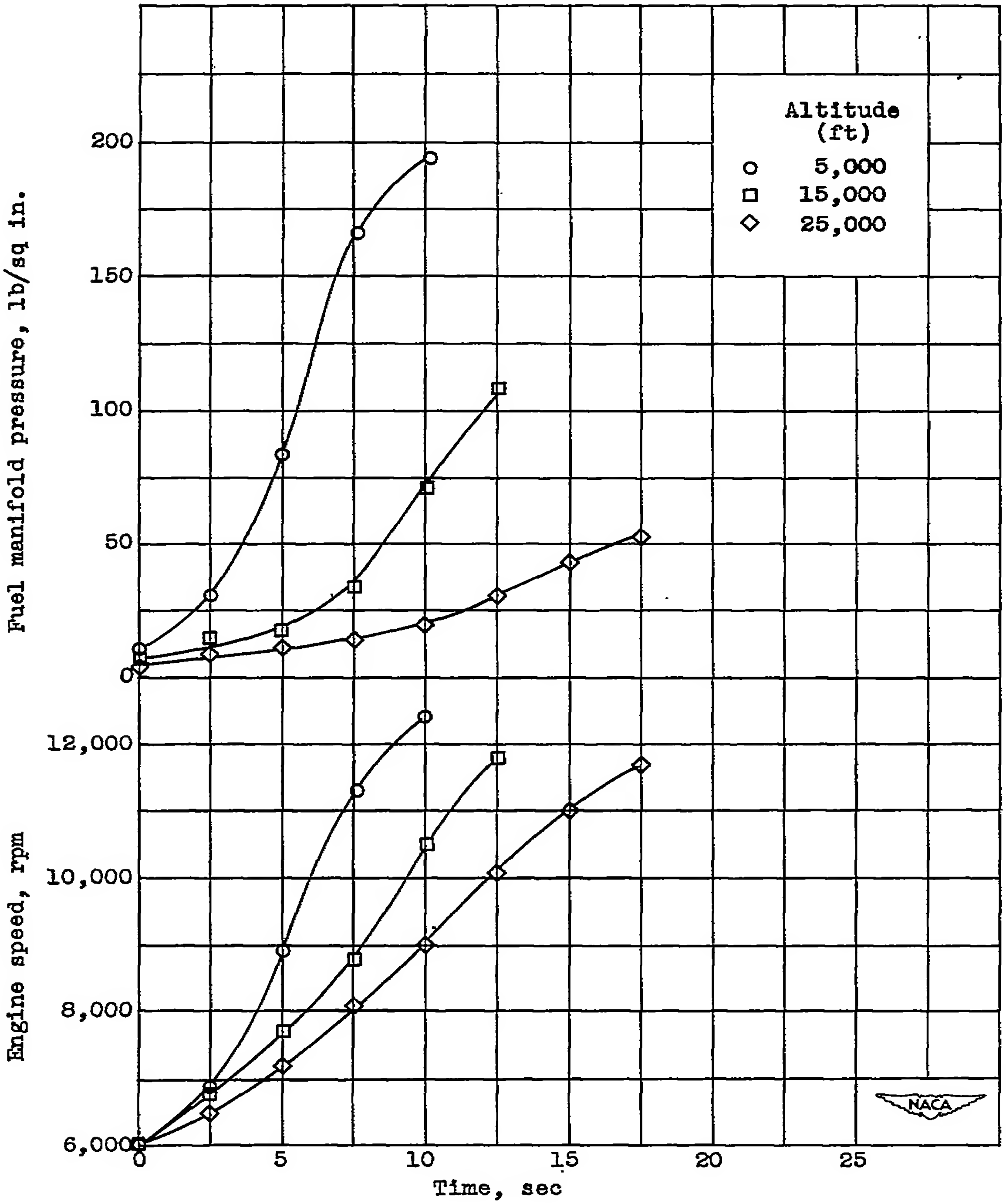

Figure 10. - Effect of altitude on time required to accelerate from 6000 to 12,000 rpm at flight Mach number of 0. Modified engine with engine governor.

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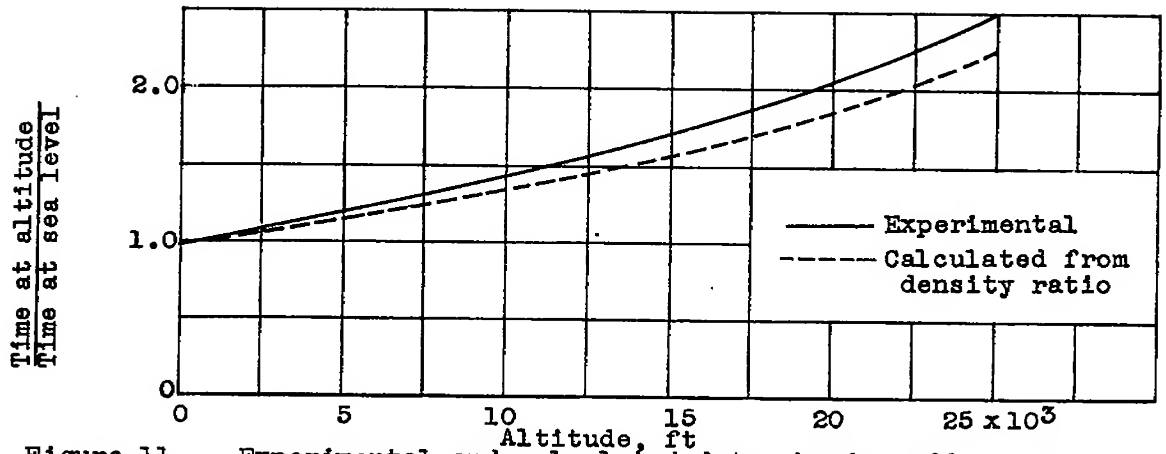

Figure 11. - Experimental and calculated data showing effect of altitude on ratio of time required to accelerate at altitude to time required to accelerate at sea level. Experimental data for modified engine and engine governor.

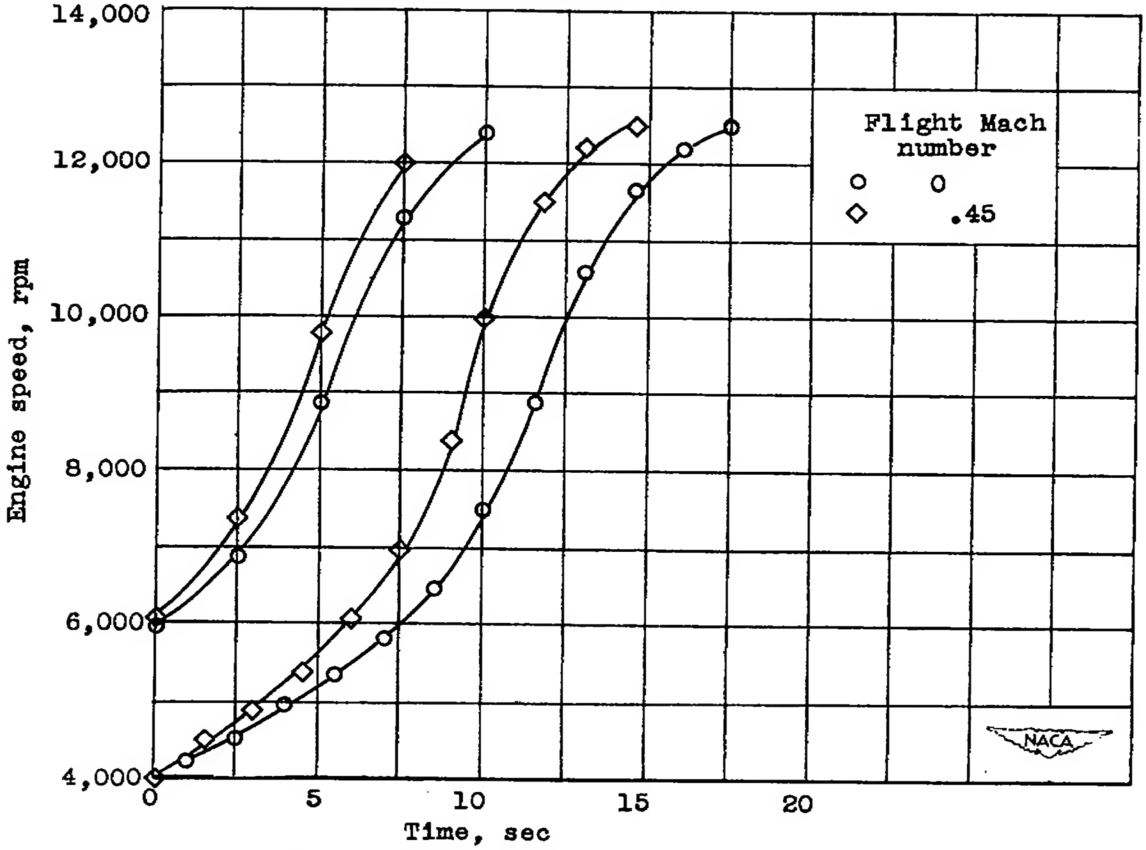

Figure 12. - Effect of flight Mach number on acceleration time at altitude of 5000 feet. Modified engine with engine governor.

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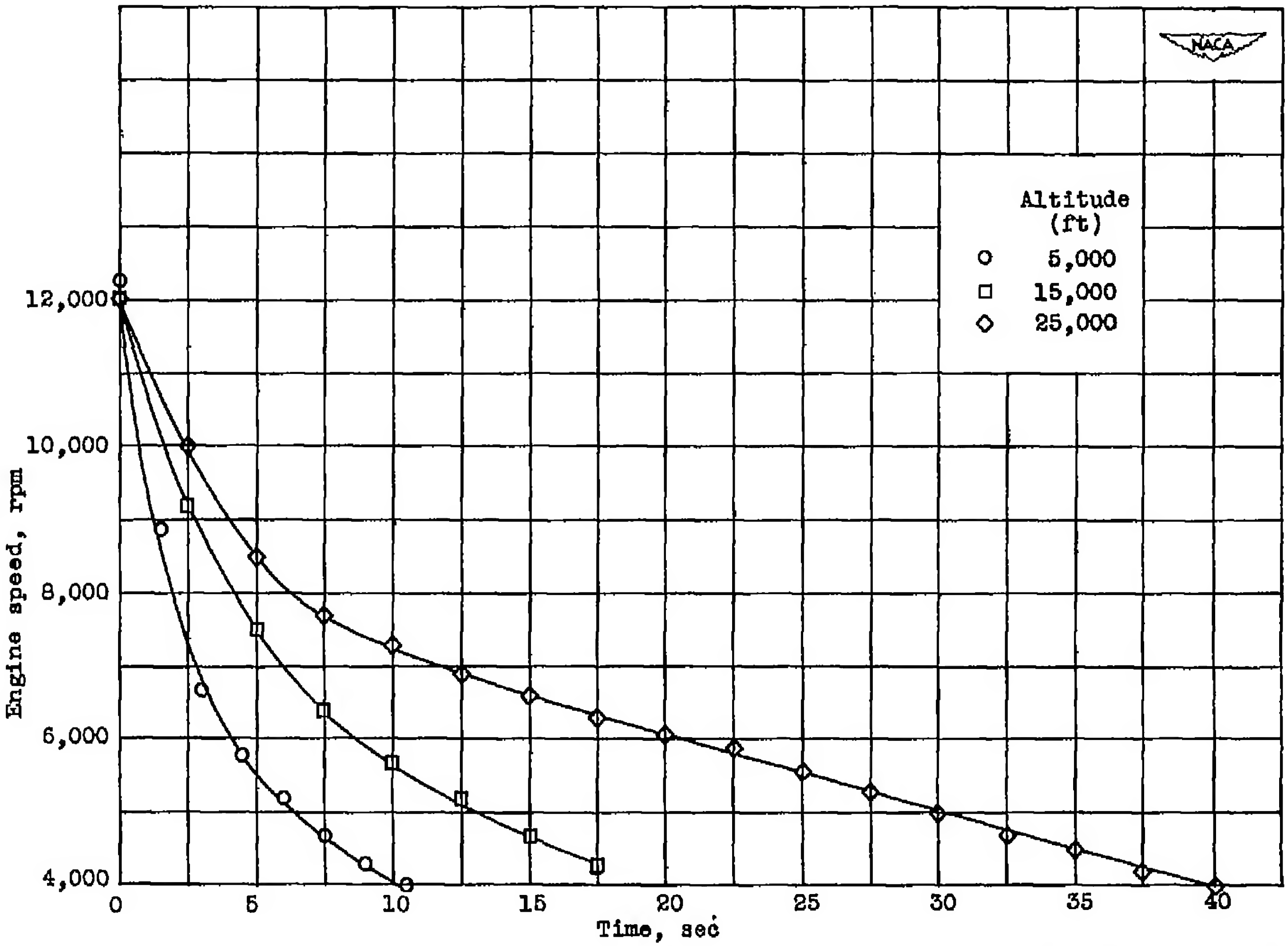

Figure 13. - Effect of altitude on deceleration at flight Mach number of 0. Modified engine with engine governor.

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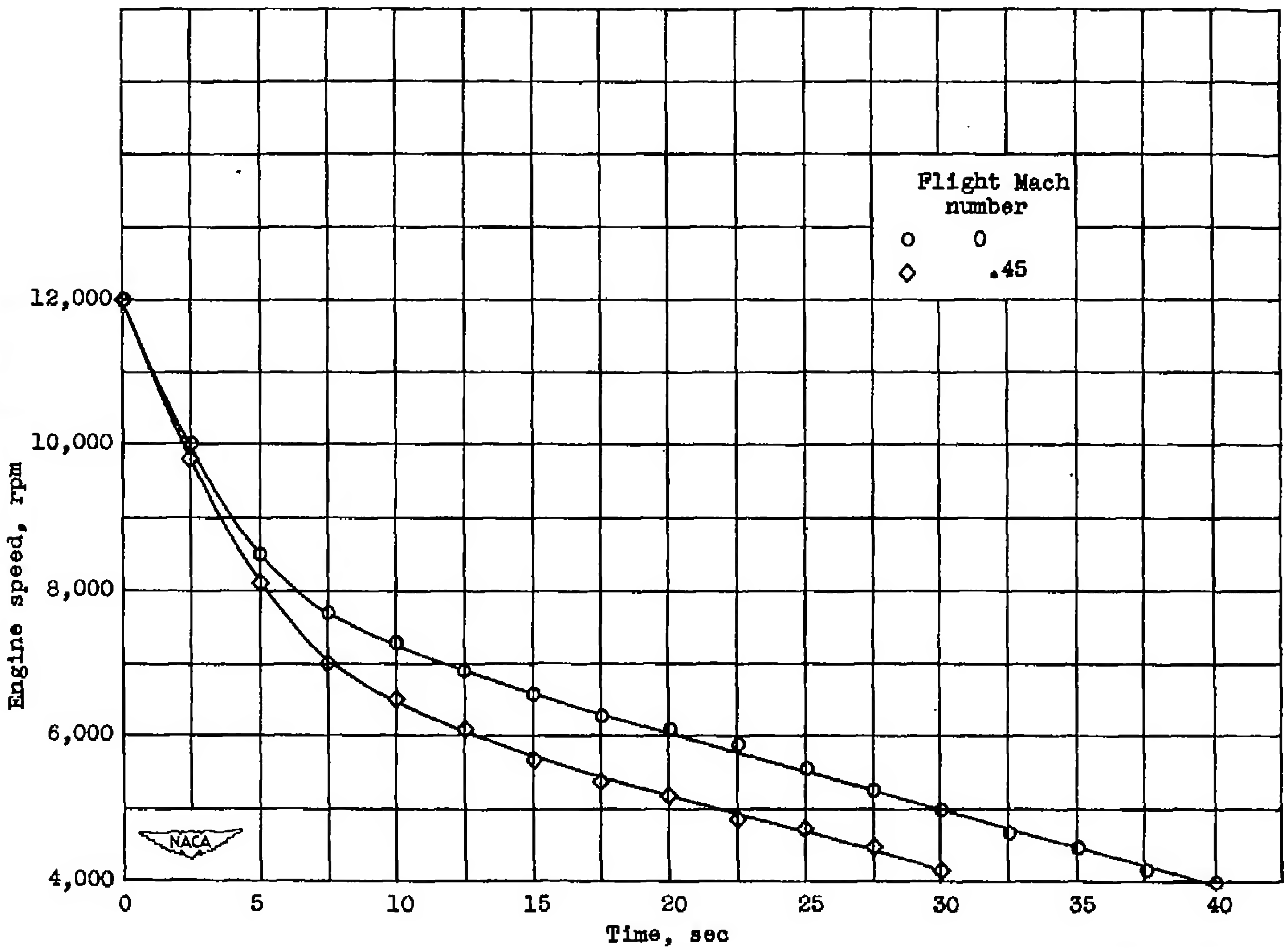

Figure 14. - Effect of flight Mach number on deceleration at altitude of 25,000 feet. Modified engine with engine governor.

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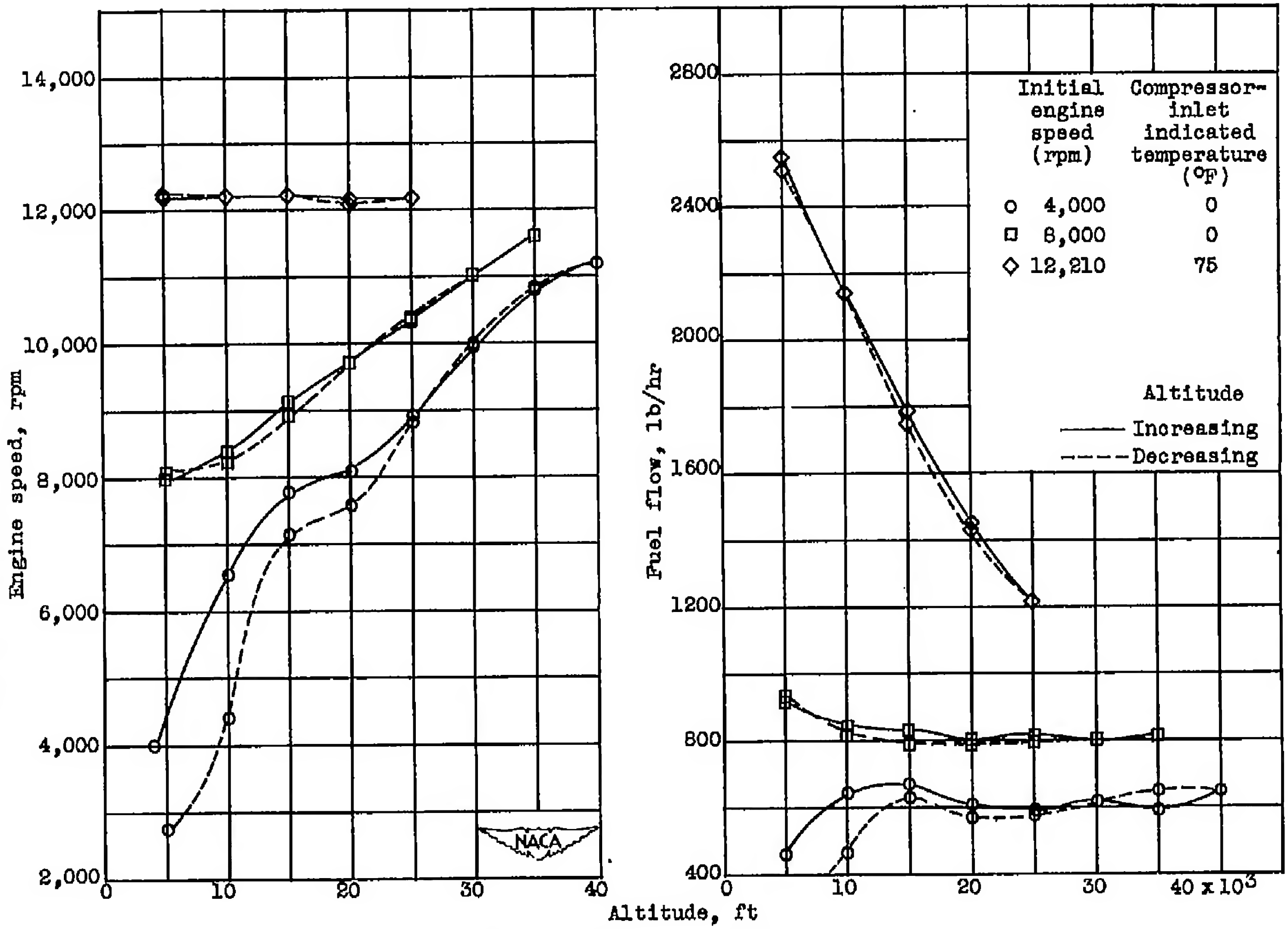

(a) Flight Mach number, 0.24.

Figure 15. - Effect of altitude on engine speed and fuel flow of modified engine with engine governor at constant throttle position.

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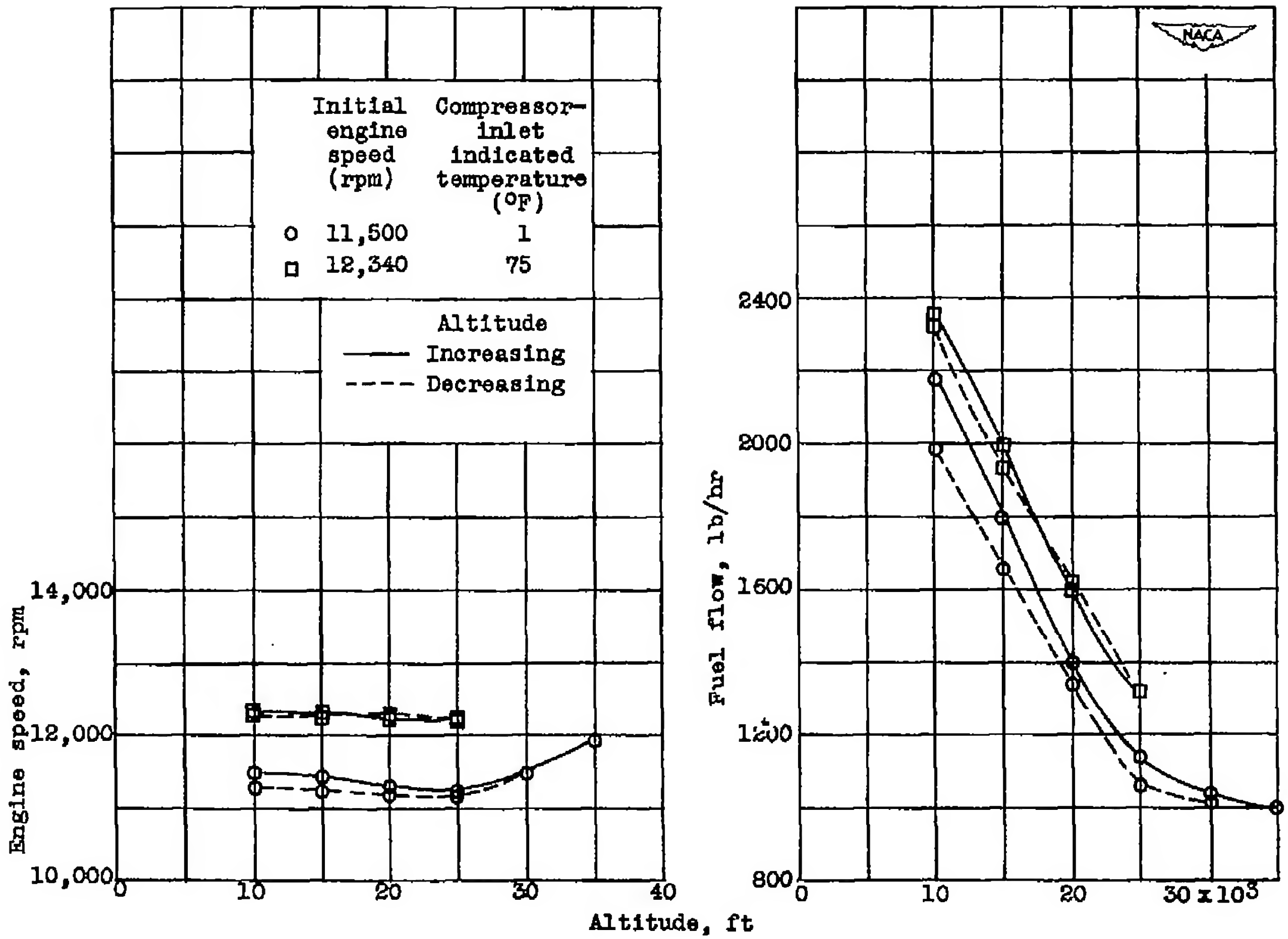

(b) Flight Mach number, 0.52.

Figure 15. - Concluded. Effect of altitude on engine speed and fuel flow of modified engine with engine governor at constant throttle position.

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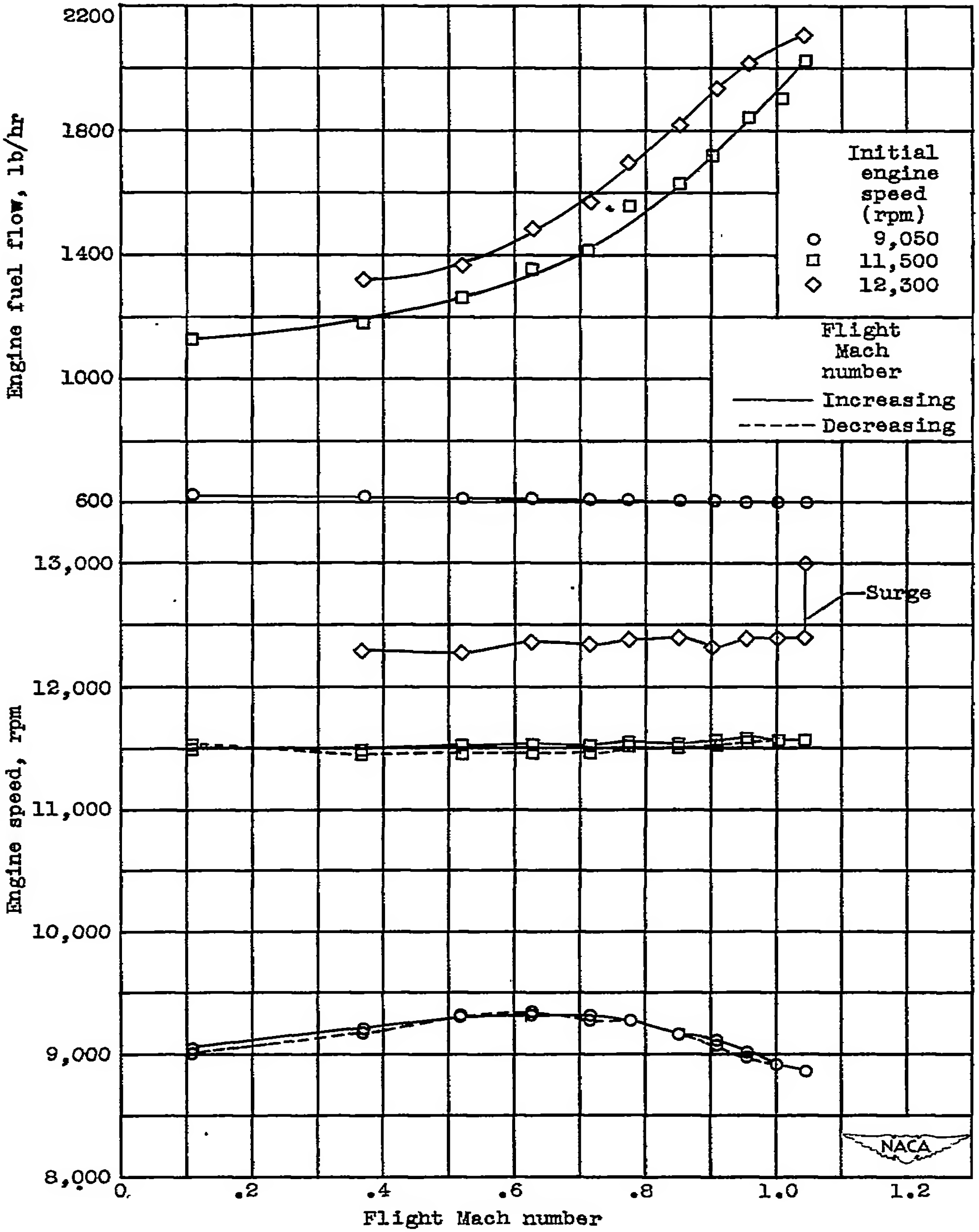

Figure 16. - Effect of flight Mach number on engine speed and fuel flow of modified engine at altitude of 25,000 feet with engine governor at constant throttle position.

[redacted]

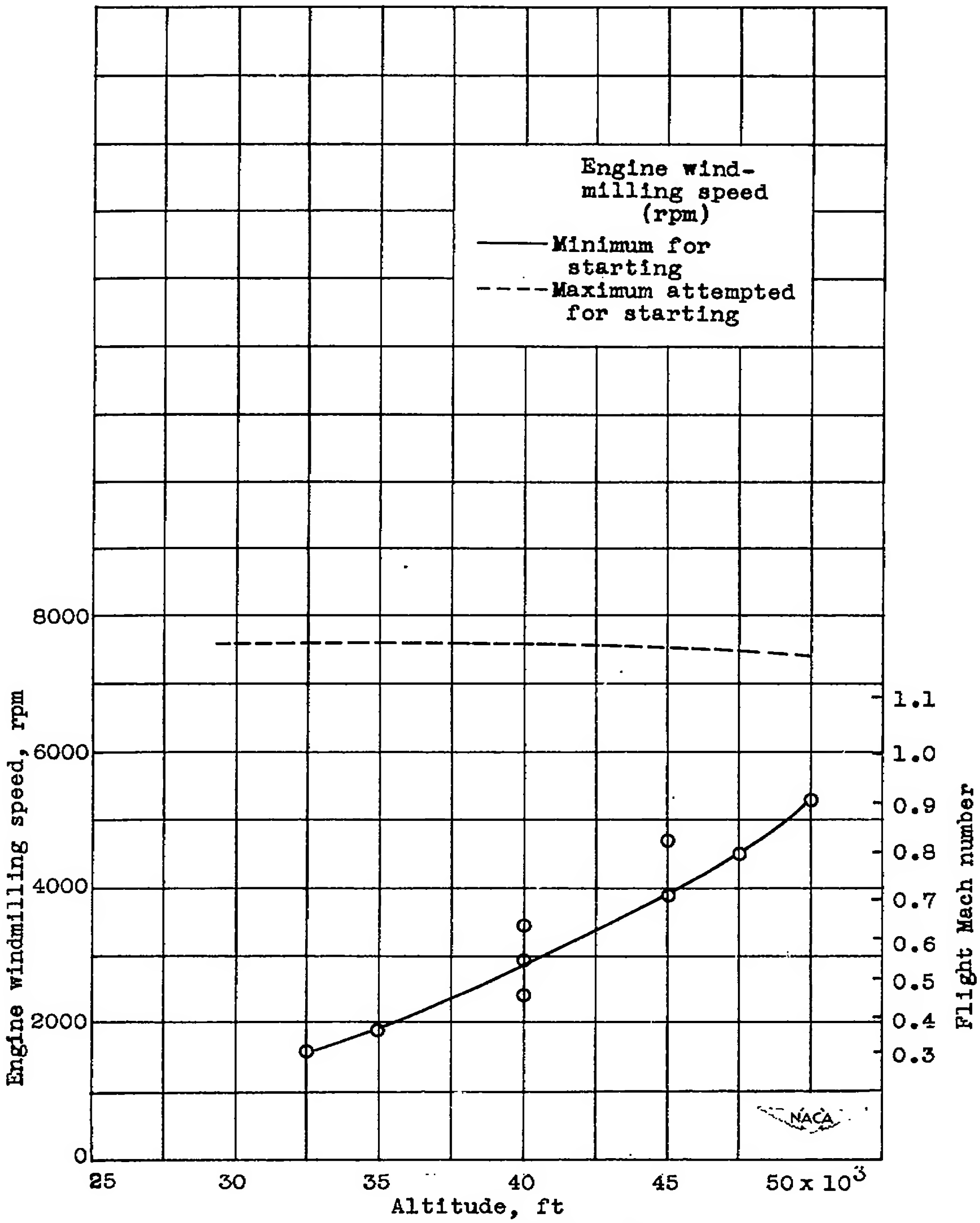

Figure 17. - Effect of altitude on engine windmilling speed and flight Mach number from which successful starts could be made. Modified engine with special fuel-control system.

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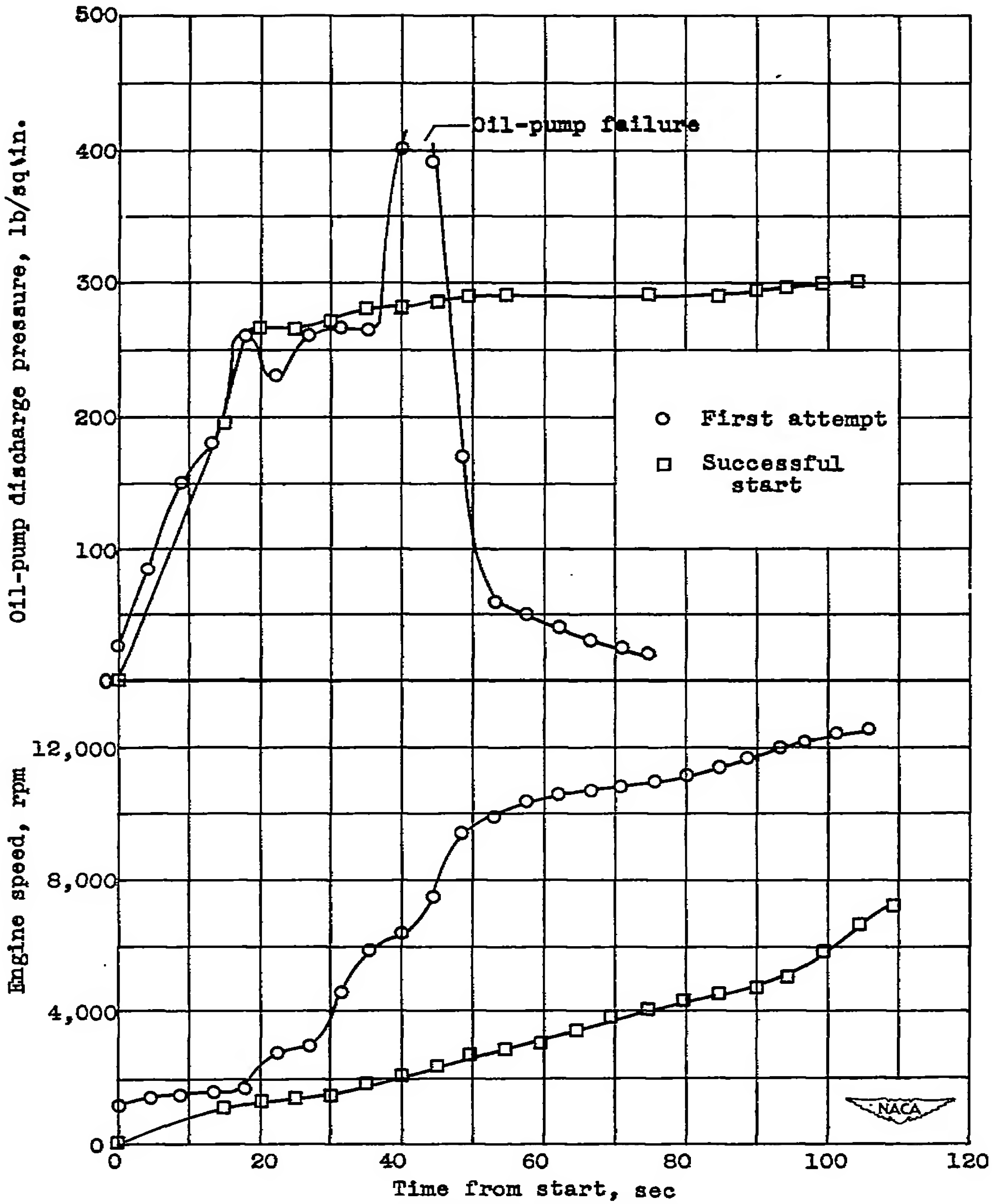

Figure 18. - Comparison of engine speed and oil-pump discharge pressure during two starts made at ambient-air temperature of -50° F with static flight conditions at altitude of 2000 feet. Modified engine with special fuel-control system.

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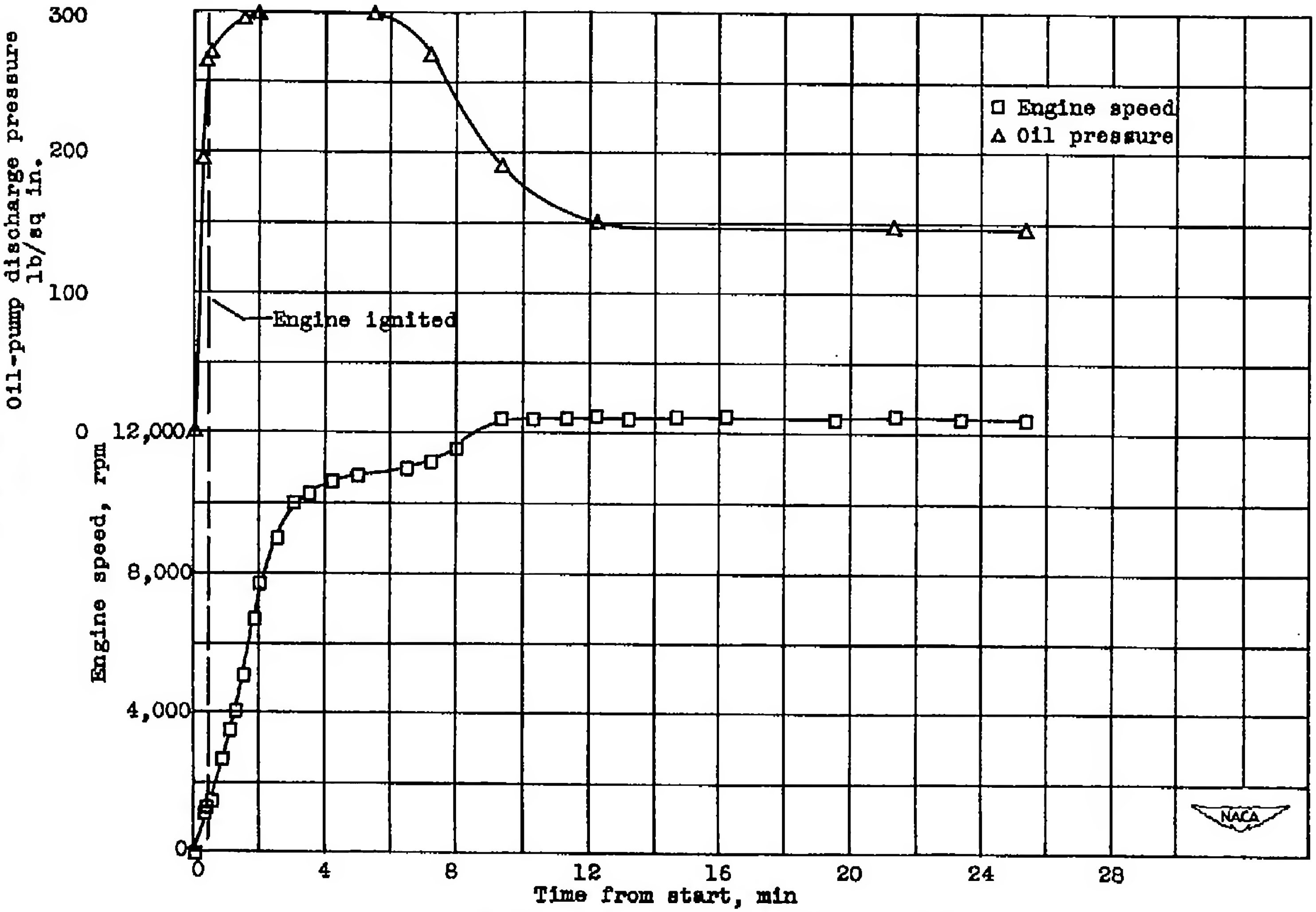

(a) Engine speed and oil-pump discharge pressure.

Figure 19. - Variation of engine speed, oil-pump discharge pressure, and bearing temperatures with time during successful start at ambient-air temperature of -50° F with static flight conditions at altitude of 2000 feet. Modified engine with special fuel-control system.

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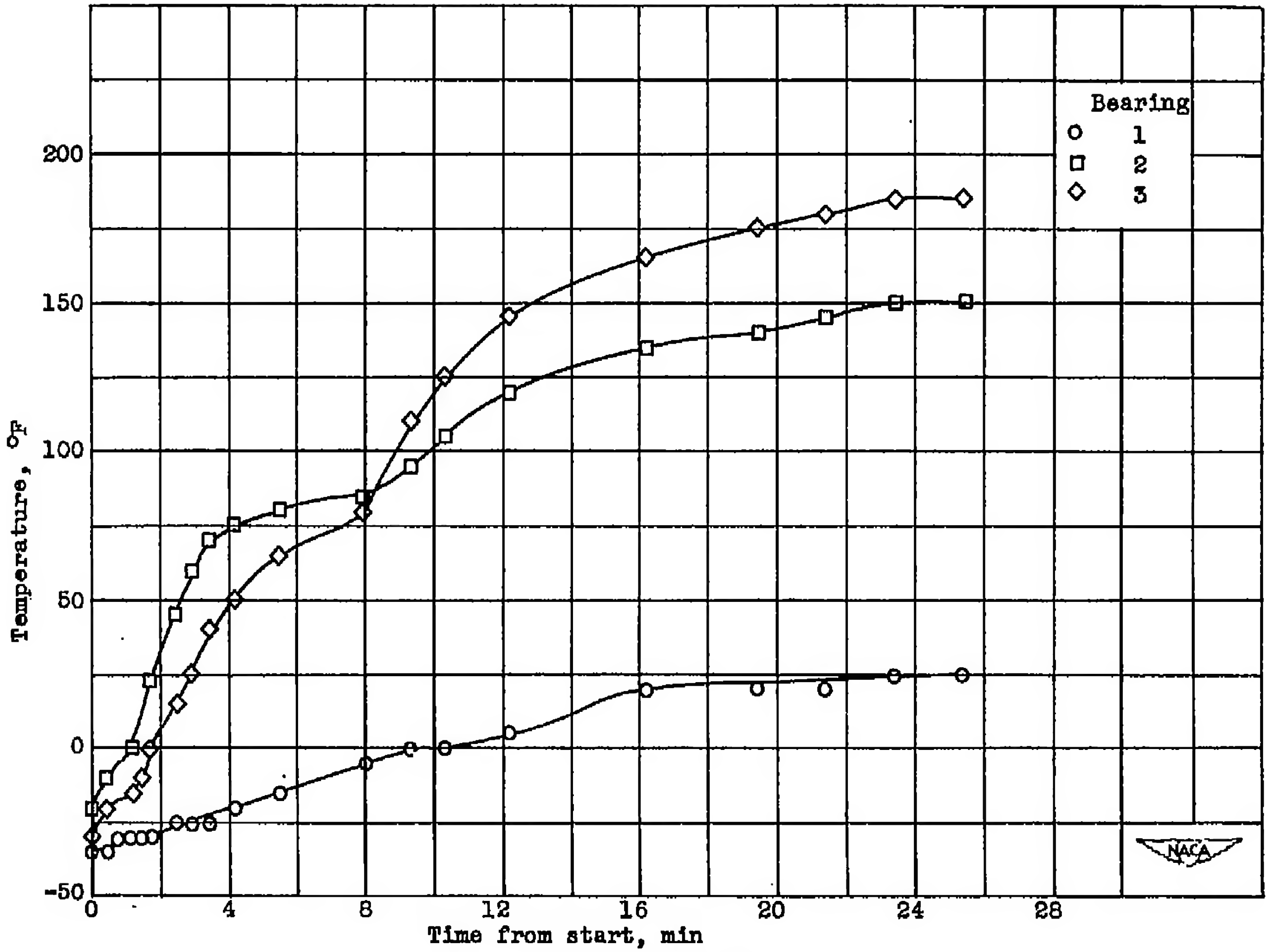

(b) Bearing temperatures.

Figure 19. - Concluded. Variation of engine speed, oil-pump discharge pressure, and bearing temperatures with time during successful start at ambient-air temperature of -50° F with static flight conditions at altitude of 2000 feet. Modified engine with special fuel-control system.